SimBRS: A UNIVERSITY/INDUSTRY CONSORTIUM FOCUSED ON SIMULATION BASED SOLUTIONS FOR GROUND VEHICLES

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ABSTRACT

The Simulation Based Reliability and Safety (SimBRS) research program focuses the efforts of a university and industry consortium in meeting the objectives of TARDEC to address the various aspects of design and simulation of vehicular systems to improve the safety and reliability related to the warfighter. The activities performed by the consortium are in support of any aspect of the TARDEC mission to create a broad range of multi-scale modeling, simulation, and validation tools and methodologies addressing reliability and safety, soldier-environment interface, biomechanics, and simulation-based design optimization. These methodologies include multi-scale experiments to optimize the robustness and reliability of the ground vehicle systems (tactical and combat) with the consideration of the human interaction. This paper will describe the present research focus of the consortium and illustrate the advantages of the consortium approach to solving complex engineering problems for ground vehicles.

BACKGROUND

The NSF Blue Ribbon Panel on Simulation-Based Engineering Science [1] reported "there is overwhelming concurrence that simulation is key to achieving progress in engineering and science in the foreseeable future." Realizing the gains in survivability that could be achieved through simulation of ground vehicle and warfighter interactions, TARDEC initiated a procurement action for forming a Simulation Based Reliability and Safety Program (SimBRS). The SimBRS program is a direct result of the U.S. Army's need for innovative solutions for reliability and safety issues that improve ground vehicle and soldier survivability for current and future tactical and combat vehicles. This "reliability research" extends the Army's budget by increasing vehicle lifespan and saving lifecycle operation and sustainment (O&S) costs for ground vehicle platforms. TARDEC's plan is to use the SimBRS contract mechanism to streamline a process that applies research funds into a managed program, that is cognizant to the relevance the Army needs for future ground vehicle platforms. In May 2008, a contract was awarded to the Center for Advanced Vehicular Systems (CAVS) at Mississippi State University, who was the sole respondent to a TARDEC market survey, to lead SimBRS. The SimBRS Program is focused to meet the Army's needs in developing advanced Modeling & Simulation tools, working through a collaborative academic & industry environment, partnering as a consortium and working with TARDEC.

SimBRS CONSORTIUM

The SimBRS consortium is a collaboration of academic and industrial research organizations that have a common mission of supporting the Army's need for ground vehicle and warfighter simulations. Different members will assume different roles based upon their areas of expertise. The challenge in any simulation based research program is to be able to have data and observations from sensors that can be used to verify and validate models (physics or empirical based) of the system being simulated.

SimBRS researchers characterize the ground vehicles, their surrounding environments, threats, and warfighters and the interactions amongst these subsystems with a network of in situ sensors and laboratory measurements. They use data from this network to describe vehicle traction, high stress concentrations and other key system features. The modelers use the resulting trend data and flow depictions to understand the underlying processes and build computational models of the vehicle system, interactions between protective devices and warfighters, and other systems contributing to safety and reliability. Over time, researchers will refine these models and assimilate them with real-time observations to predict failures of components and overall safety and reliability of the integrated system of vehicle and warfighter.

Initially, the partners in the SimBRS consortium consisted of HBM – nCode, Lawrence Technological University, Mississippi State University, University of Notre Dame, University of Alaska Fairbanks, and Western Michigan University. Subsequently, Caelynx LLC, PTC, and Ricardo Inc. have all been added to the team.

The SimBRS program intends to impact all ground vehicle platforms, existing and new, through recap/reset, or through

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14. ABSTRACT
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15. SUBJECT TERMS

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improvements in original designs. Its greatest impact is expected to lead to and leverage new vehicle designs. Therefore, the challenge for the SimBRS team is to establish an approach based on the capacity of measured data and simulations to support decision-making by the Army in establishing policies and management solutions for current and future ground vehicles. This decision-making is driven by systematically relating appropriate results from measurements and applied research in engineering and science. In turn, basic research and technology developments in areas such as materials science and energy enable applied research. The relationship among basic research and development, applied research, and operational solutions is dynamic and iterative and requires a systematic approach to bridge the gaps between the research and operational domains.

AN APPROACH

The SimBRS scope of work defined a list of nineteen (19) level of effort tasks that encompass many aspects of ground vehicle and warfighter survivability. The activities performed by the consortium are in support of any aspect of the U.S. Army Tank Automotive Research, Development and Engineering Centers (TARDEC) mission to create a broad range of multi-scale modeling, simulation, and validation tools and methodologies addressing reliability and safety, soldier-environment interface, biomechanics, and simulation-based design optimization. These methodologies include multi-scale experiments to optimize the robustness and reliability of the ground vehicle systems (tactical and combat) with the consideration of the human interaction. They are listed below.

- Multi-Scale Metal Component Reliability/Safety
- Multi-scale Biomechanics Reliability Model Development
- Structural Composite Design and Reliability/Safety
- Joint/fastener and Systems Reliability
- Simulation-Based Design Optimization for Component Reliability
- Simulation-Based Design Optimization for System Level Reliability
- High Performance Computing Incorporating Physics-Based Reliability and Safety Models
- Cyberinfrastructure
- Reliability Networking and Sensory-Based Health Monitoring for Field Applications
- Human Factors Development and Evaluation
- Computer Aided Engineering Tools for System Level Reliability
- Occupant Safety and Crashworthiness Research, Development and Testing
- Blast and Fragmentation
- Hybrid Vehicle System and Component applicability and reliability
- Simulation Integration
- Verification and Validation
- Supercomputing Processes
- Electronic Systems and Network reliability
- Vehicle/Terrain Modeling

To better manage these tasks, the SimBRS Consortium defined five (5) research thrusts around which it built its research program in support of TARDEC's Mission and Vision. These areas are:

- Multi-Scale, multi-physics modeling for vehicle dynamics and structural reliability, durability, and survivability
- Warfighter based simulations for survivability
- Validation, verification, and accreditation of models and simulations
- System Integration and Optimization: Hybrid technologies
- Simulation of fluid-structure interactions

The rest of the paper will describe some of the on-going work in the various research thrusts and one task will be more fully elaborated upon to show readers the depth of the modeling and simulation activities within SimBRS.

MULTI-SCALE, MULTI-PHYSICS MODELING FOR VEHICLE DYNAMICS AND STRUCTURAL RELIABILITY, DURABILITY, AND SURVIVABILITY

The University of Notre Dame has a task entitled Hybrid Cellular Automata for Vehicle Structural Design for Improved Soldier Crash Safety and Survivability. The objective for this work is to develop and demonstrate new computational design methodologies for topologically controlled crashworthiness design synthesis for improved soldier survivability subject to nonlinear transient loadings and blast loadings. Additional objectives include; the development of multi-scale nano-composite simulations for multi-scale material design; the development of high-temperature rapid reactive pressing techniques for improved materials joining; the development of energy absorbing structural concepts for occupant protection; and the development of hybrid welded/woven processing for improved material joining. In this same thrust area, Mississippi State University has a task to develop coupled computer-aided-engineering (CAE) simulation methodologies and to conduct high strain rate material characterization to evaluate explosive blast and fragmented shrapnel effects on ground vehicle structures.

WARFIGHTER BASED SIMULATIONS FOR SURVIVABILITY

Mississippi State University has a project for a Side Curtain Air Bag Computer-Aided-Engineering (CAE) Modeling Study. The objective of this research is to investigate and perform a parametric study related to side curtain air bag interaction with an out-of-position occupant (crash test dummy) simulating a crash event. Another project at MSU seeks to improve the fidelity of human behavior modeling and visualization in the TARDEC Ground Vehicle Simulation Lab (GVSL) in Warren, MI. This work is focused upon the current digital human modeling capabilities within TARDEC GVSL using the OneSAF behavior modeling framework. MSU is replicating the form, fit, and function capabilities of the TARDEC GVSL through the implementation of identical software configurations for the TARDEC GVSL software framework using: OneSAF Objective System, SimCreator, and Delta3D software. After development of the scenarios, MSU will demonstrate the capabilities of these new TARDEC GVSL scenarios at the MSU CAVS and also at the TARDEC GVSL. The demonstrations of these scenarios will show more realistic human behavior modeling and visualization; thereby contributing to a more realistic simulation for the soldier participants.

VALIDATION, VERIFICATION, AND ACCREDITATION OF MODELS AND SIMULATIONS

HBM nCode is working on a project entitled, Improved techniques for vehicle prognostic/diagnostic data acquisition, analysis, and storage. Western Michigan University is developing state-of-the-art computer tools for use in modeling and simulation (M&S) to advance the prediction of ground vehicle reliability and safety in extreme operating environments. A wireless, self-sufficient and cost-effective vehicle health management system using off-the-shelf devices for tactical vehicles is being developed. The research is focused on engine, engine coupling, transmission, drive shaft system, differential, axle, and wheels and tires. Lawrence Technological University is enhancing its test capabilities for vehicle armor and vehicle sub-systems with the addition of an environmental chamber.

SYSTEM INTEGRATION AND OPTIMIZATION: HYBRID TECHNOLOGIES

MSU is investigating Advancements in Ob-Board vehicle Power (OBVP). This effort is optimizing OBVP and increasing the reliability of OBVP through:

- Improving upon the power density associated with the converter/inverter for engine driven applications
- Investigating modifications to both vehicle, speed controller, and power converter to facilitate mobile, “on the go” applications for OBVP, and
- Developing and evaluating non-belt-driven advanced electromechanical energy conversion subsystems to achieve up to engine-limited power levels from the vehicle.

SIMULATION OF FLUID-STRUCTURE INTERACTIONS

MSU, Notre Dame, and Western Michigan University have projects in this thrust. However, the task MSU has for Simulation of Blast-Vehicle Interactions will be more fully developed for this paper.

Modeling Blast-Soil Interactions

Soil plays an important role in characterizing landmine or IED explosive loads. The soil can both dissipate as well as focus explosive energy. In addition, the ejected soil material can comprise a significant fraction of the impulse loading on the vehicle. Roughly speaking soil can be classified into two general categories: cohesionless (sandy) soils and cohesive (clayey) soils. Each type of soil brings its own modeling requirements. There have been significant investigations into modeling blast-soil interactions. Most of these models have employed general purpose simulation codes such as LS-DYNA or AUTODYN with soil modeled as a solid material with specific equation of state and strength models [2, 3, 4, 5, 6, 7, 8, 9, 10]. In all of these models, the soil material was treated as a plastic solid material. The explosives burst through the overburden due to material damage, where the typical failure models were based on a simple limit on the tensile strength. The three components of most of these models included an equation of state, a strength model, and a failure model. Fiserova gives a detailed account of many of the modeling approaches [2].

In most of the soil models a three phase mixture of solids, water, and air are used to obtain the equation of state [2, 10, 11]. These equations of state are typically implemented by prescribing a look-up table defining a density vs. pressure relationship. In addition, a soundspeed vs. density relationship was prescribed. In most of these models, values from lower pressures were extrapolated to high pressure regimes where no experimental data was available. For strength models, some developed sophisticated models based on mechanistic analogies of springs and dampers to describe the soil micro-structure response [10].

There are several common themes in all of the above models. First, all of the models make use of a three-phase model to derive an equation of state, but do not represent the soil as a multi-phase model in the sense of having independent velocities for the different phases. Thus, the explosive gases released by detonation do not pass through a cloud of soil particulates, but instead the soil is torn open by the blast allowing the explosive gases to escape (along with some chunks of soil). In addition, depending on how the damage progresses through the soil, some of the soil may become eroded through the use of free nodes. These free nodes can then continue on their trajectory and impact nearby surfaces. However, this numerical approach is not particularly physical, and certainly doesn’t respect the full complexity of a more complete multi-phase model.

The approach we have taken is to employ an Eulerian description of the blast-soil problem and incorporate it into the Loci/CHEM flow solver [12]. Loci/CHEM is a full-featured Navier-Stokes simulation code that was developed to simulation chemically reacting flow. One of the first considerations is the evaluation of the thermophysical properties of a mixture of materials. The implementation of the mixture rule can affect interface dynamics as well as the numerical robustness of the solver. Our mixing rule assumes that our materials are immiscible and are in mechanical (pressure) and thermal equilibrium. In this mixing rule we assume that we have a mixture of species equations of state which define pressure as a function of density and temperature. The equation of state for a perfectly elastic solid is defined by a simple linear barytropic equation of state and the equation of state for water is modeled using the Tait EoS, which is a simple and accurate barytropic equation of state for liquid water under high pressure.

One challenge with simulating multicomponent flows is that it is possible to take a time-step such that the material in a cell is completely depleted resulting in the time evolution of negative mass fractions of material. This non-physical circumstance is unacceptable as it makes it nearly impossible to advance the solution. For first-order spatial approximations, it is guaranteed not to deplete the material from a cell provided a time-step is employed that satisfies the stable CFL condition. However, when reconstructing higher-order mixture fractions, it is possible to deplete a material even when using a much smaller time-step To allow for second-order spatial reconstruction of species mass fractions, we first limit the mass fraction extrapolations so that a negative mass fraction would not occur (assuming a first-order upwind convection). While such limiting helps to avoid the evolution of negative mass fractions, they can still evolve. To prevent this evolution we limit the stable time-step to include the time required to deplete a cell of all of a species material using the first time-step residual. This provides an effective strategy that avoids negative mass fraction evolution in the time-stepping algorithm. However, for multicomponent simulations a CFL setting between 0.75 and 0.5 may be required to avoid the evolution of negative mass fractions.

Sample Results I: Small-Scale Explosion in Dry Sand

We have performed validation studies for 100g of C-4 buried at a depth of 30mm in dry sand. Figures 1-3 show comparisons of displacement parameters between our simulation results and measurements. Predictions from AUTODYN and LS-DYNA are also included in the plots. Figures 1 and 2 show the height and width of the detonation products cloud, respectively. The agreement between simulation results and experimental data are very good in both cases. We note that at longer times, our model under-predicts values relative to the experimental data. We suspect that this may be due to a lack of failure mechanism for the soil. In our simulations, the soil encloses the growing cloud of detonation products, whereas in the AUTODYN simulations the soil ruptures thereby releasing the explosive products. In our method, the soil remains in velocity equilibrium with the explosive gases. Figure 3 shows the temporal variation in the crater diameter. Fairly good agreement is achieved between the simulation and the measurement. At later times, our simulations over-predict the crater diameter by approximately 30 percent. It is likely that at later times the lack of a soil strength model is responsible for this discrepancy: At these later times, the strain rates diminish, which increases the relative importance of the material strength in the material kinematics.

Sample Results II: Mine Impulse Pendulum (MIP) Explosion in Prairie Soil

The mine impulse pendulum is a horizontal ballistic pendulum that measures the effective impulse from a landmine explosion. The experiment was performed using

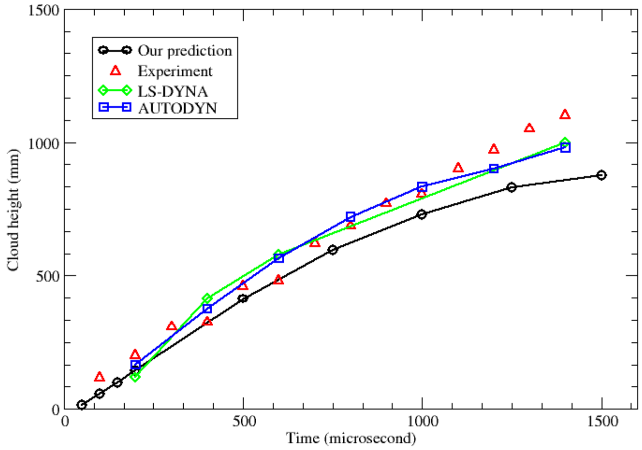

Figure 1: Time history of the height of the detonation product.

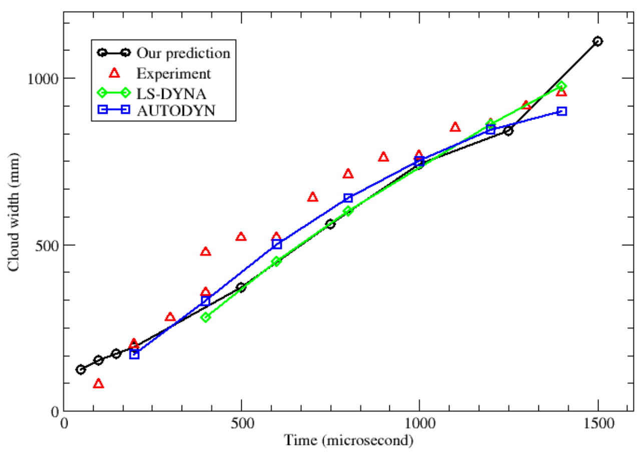

Figure 2: Time history of the width of the detonation product.

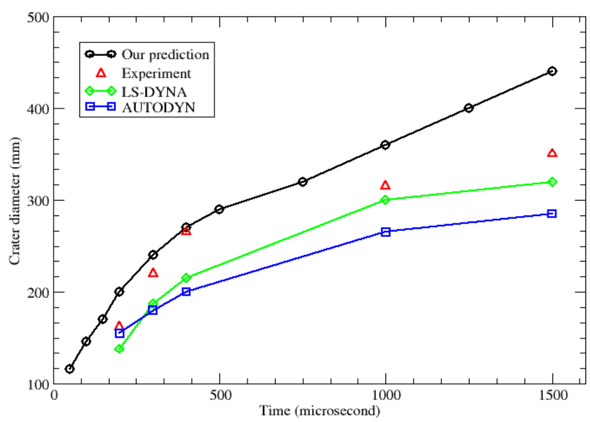

Figure 3: Time history of the width of crater.

DRDC Suffield's small pendulum apparatus [13]. The pendulum consists of a target plate attached to two rotating steel beams affixed to a stationary base. The pendulum target plate is suspended at certain standoff distance over a buried landmine. The landmine is detonated, and maximum angle of inclination obtained by the pendulum arm is measured, and effective mechanical impulse applied to the target by the landmine can be derived as a function of the maximum inclination angle of the pendulum. Details describing the MIP experiment can be found in the PhD dissertation of Fiserova [2].

Figure 4 shows a comparison of impulse on the target plate versus soil moisture content for a 50mm overburden landmine explosion. Simulation results from AUTODYN and Martec's Chinook code [8] are also included for comparison purposes. We note that the formulation of the Chinook code is very similar to the methodology that we employ: it employs algorithms typically used to solve inviscid gas dynamics equations. It is shown in the figure that the trends of increasing impulse as a function of moisture content are consistent with that of the experimental data qualitatively. The trend of increasing impulse with increasing moisture content is reproduced. However, it is seen that our simulations over-predict the impulse by 5 to 50 percent in comparison with the experimental data. Results from AUTODYN are smaller in magnitude than our predictions and, in general, show good agreement with the experimental data.

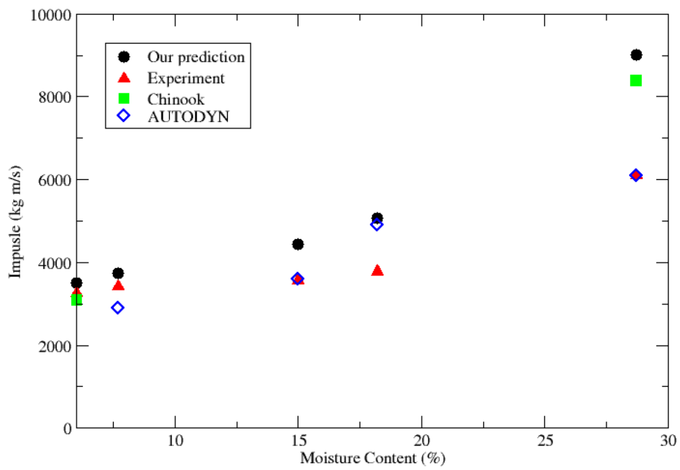

Figure 4: Comparison of impulse on the target plate for *DOB*=50*mm.*

Observations for Future Investigations

We note from the small-scale dry sand validation of the evolution of the crater and the ejecta cloud that there is some evidence that material strength may play an important role in the later times of the soil-blast evolution. The algorithms that we currently employ have been developed primarily for accurate gas-dynamics simulation and so including strength is more challenging. Specifically, we track material velocity rather than material deformation, therefore strain is not directly available. However, development of strength models in the context of a Godunov type solver similar to the algorithm employed here has been developed [14] and could be adapted for our model with modest effort.

A second critical feature that is lacking in our simulation is a more correct modeling of the transition to multiphase flow of soil during the explosive interaction. In existing failure models, material is removed from the simulation. We propose that, instead of being removed, the soil should transition into a multiphase cloud and allow the solid soil material to take on independent velocity groups from the gas phase. We are now extending our model to inject multiphase particles into the simulation and track them using a Lagrangian approach. Transition to multiphase would occur based on criteria similar to failure, e.g. if soil material pressure (or density) dropped below a given threshold, we can assume that the soil decohesion results in a dense multiphase cloud. Such a model would allow for a decoupling between the soil particle and gas velocities which should result in a more rapid growth of the detonation cloud. Additionally, we expect that inclusion of these effects will improve our model performance on the MIP validation case.

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